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EMPIRICAL METHODS FOR FORECASTING THE MAXIMUM STORM TIDE DUE TO HURRICANES AND OTHER TROPICAL STORMS

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1. INTRODUCTION

Of all the causes of death and destruction from tropical storms the most treacherous is the rise in sea level associated with the landfall of the storm, a phenomenon known as the storm surge. This is true because the rise in sea level along the coast in flat regions may lead to the penetration of the sea 10 to 20 miles inland. Not only are regions near the coast flooded by the intrusion of salt water, but erosion processes due primarily to wave action are effective inland far beyond the normal coastline. Occasionally, significant breaks in barrier reefs are produced by the combination of erosion due to wave damage and the storm surge.

Another factor in the insidious behavior of the storm surge is that the surge generated on the open coast must move inland as a gravity wave, and thus the peak disturbance at the end of a long channel, such as Long Island Sound, may occur many hours after the other signs of hurricane fury have begun to diminish. Interaction with the astronomical tide also may cause the most severe flooding to occur several hours before or after the peak intensity of the storm.

The extent of coastal flooding produced by hurricanes along the open coast depends on the wind field, the pressure deficiency, the size and speed of motion of the storm, the bottom topography near the landfall of the storm, and the astronomical tide (Harris [4] and Reid and Wilson [9]). The disturbance generated in open water is further modified by convergence or divergence of the surge and local wind setup, seiching, and perhaps rainfall runoff in the mouths of rivers and other estuaries.

The forecast centers do not have the facilities required for a full consideration of all these factors in the time available for a forecast during a hurricane threat. Accordingly it has been necessary to seek some empirical procedure which combines a number of these effects into a single parameter to give an estimation of the extreme tide to be expected with any hurricane.

2. DERIVATION OF EQUATIONS

Since the data from a large number of storms must be combined, and detailed data concerning the structure of a storm are rarely available before the storm moves inland, only a simple storm model can be used. The simplest model which appears reasonable is one in which the pressure depends only on the distance from the center of the storm. With such a storm, the maximum wind speed depends on the pressure deficiency. Near the center of the storm the cyclostrophic effect greatly exceeds the geostrophic and the maximum wind speed (V_{max}) can be taken as

$$V_{max}=K(p_n-p_0)^{1/2} \tag{1}$$

where p_n is the pressure at the edge of the storm; p_0 is the pressure at the center of the storm, and K is a constant of proportionality. Equation (1) has been given by Myers [7], Fletcher [3], and others. A study of the maximum wind speeds in Gulf of Mexico hurricanes, made at the New Orleans Forecast Center [2] several years ago, showed that the results obtained by holding p_n constant at 1005 mb. were not significantly inferior to the results obtained by using a variable p_n. For several years the equation

$$V_{max}=75\sqrt{(1005-p_0)/12} \text{ for } (1005-p_0)>12 \qquad (2)$$

where V_{max} is given in miles per hour and p_0 in millibars, has been used by the New Orleans Forecast Center [2] to estimate the extreme wind speed to be expected in a hurricane. Equations of similar form have been found empirically by Takahashi [10] and others for typhoon winds.

The setup due to wind should be proportional to the wind stress. According to many writers the wind stress, τ, should be given by

$$\tau=\rho\gamma^2V^2 \qquad (3)$$

where ρ is density of the air, γ^2 is the wind stress coefficient, depending on the surface roughness, and V is the wind speed. Neumann [8], noting that the surface roughness over water depends on the wave height, which in turn depends on the wind speed, prefers an expression of the form

$$\tau=\rho AV^{3/2} \qquad (4)$$

where A is a constant. Others writer (Montgomery [6]) have preferred other values for the exponent of V and have given the total setup h in the form

$$h=BV^{2b} \qquad (5)$$

where B and b are constants to be determined from the data. Combining (1) and (5), we obtain,

$$h=B(p_n-p_0)^b \qquad (6)$$

Equations (1) and (3), when combined with equation (6), imply that $b=1$. In this case we can write (6) in the more usual form for regression equations:

$$h=a+b'p_0 \qquad (7)$$

Equations (1) and (4), when combined with (6), imply that $b=3/4$. Reid and Wilson [9], working with a very simple hurricane model, found that with a continental shelf of constant slope, b could equal 3/4 even with equation (3). Their results depended on their assumed model hurricane, slope of the continental shelf, and wind stress law. This implies that in a purely empirical study such as this, one might expect to obtain better results by assuming that B and b are both arbitrary constants to be determined from the data. This can be accomplished most simply by taking the logarithm of both sides of equation (6) to obtain

$$\log h = \log B + b \log (p_n - p_0). \qquad (8)$$

This is of the form $y = a + bx$, and a and b can be obtained by the method of least squares.

3. APPLICATION TO GULF HURRICANE DATA

The logic of this derivation shows that it should be expected to apply to the storm surge; that is, to the difference between the observed storm tide and the astronomical tide. Also it should apply only to the maximum tide on the open coast uninfluenced by convergence or oscillations in bays. The exact time of the peak surge on the open coast is generally unknown, even when the maximum water level is known, so that corrections for the astronomical tide are often impossible when dealing with the records of past storms. However, the range of tide in the Gulf of Mexico is generally small, usually less than one foot, and the observed departure from mean sea level provides a useful approximation to the storm surge during exceptionally high tides.

The selection of the particular report which best represents the extreme tide height on the open coast, with a minimum of local influences due to estuarian effects, is somewhat subjective, and no two workers will agree completely on all cases. Nevertheless, reasonably satisfactory data have been found for 30 hurricanes entering the United States from the Gulf of Mexico prior to 1956. Some of these data were obtained from Cline [1] and Hubert and Clark [5]. Many were obtained from hurricane survey reports now being prepared by the U. S. Army Corps of Engineers. Others were obtained from hurricane descriptions in early editions of the *Monthly Weather Review* or from Coast and Geodetic Survey records.

These data are listed in table 1 and plotted in figure 1 as a function of the central pressure of the storm as it crossed the coast. The central pressures were taken from table 3–1, U. S. Weather Bureau [12] except where otherwise noted. No reliable reports of the maximum water levels were obtained for storms with lowest pressure below 934 mb. The "Labor Day" hurricane of 1935 had a reliably reported minimum pressure of 892 mb., the lowest sea level pressure reported in the United States, and was attended by a storm wave whose height has been estimated at 15 to 20 ft. above mean low water (Tannehill [11]). This value has been adjusted to mean sea level and is plotted as a range in figure 1, as this is the best available data for extending the range of the prediction curve.

If the data in table 1 are analyzed according to equation (6) and p_n is taken as 1005 mb. as in equation (2), the resulting equation* is

$$h_{max}=0.867(1005-p_0)^{0.618} \qquad (9)$$

*An empirical system similar to that described in this paper has been used at the Weather Bureau Forecast Center in New Orleans for several years. With the data first obtained [2], this equation took the form

$$h_{max}=\tfrac{3}{4}(1005-p_0)^{2/3}$$

The maximum storm tide in hurricane Flossy of 1956 was successfully forecast by this equation.

TABLE 1.—*Lowest central pressure and highest tides of Gulf of Mexico hurricanes.*

	Date	Location of highest tide on open coast	Lowest pressure (mb.)	Maximum tide height (feet)
1	Oct. 2, 1893	Mobile, Ala	956	8.4 m. s. l.
2	Sept. 8, 1900	Galveston, Tex	936	14.5 m. s. l.
3	Aug. 14, 1901	Mobile, Ala	973	7.4 m. s. l.
4	Sept. 27, 1906	Fort Barrancas, Fla	965	10.8 m. s. l.
5	July 21, 1909	Galveston, Tex	959	10.0 m. s. l.
6	Sept. 20, 1909	Mobile, Ala	980	7.8 m. s. l.
7	Sept. 13, 1912	Mobile, Ala	*993	4.4 m. s. l.
8	Aug. 16, 1915	High Island, Tex	953	13.9 m. s. l.
9	Sept. 29, 1915	Grande Isle, La	944	9.0 m. s. l.
10	July 5, 1916	Fort Morgan, Ala	961	4.7 m. s. l.
11	Sept. 28, 1917	Fort Barrancas, Fla	964	7.1 m. s. l.
12	Sept. 14, 1919	Port Aransas, Tex	948	11.1 m. s. l.
13	Oct. 25, 1921	St. Petersburg, Fla	958	7.8 m. s. l.
14	Aug. 25, 1926	Timbalier Bay, La	959	10.0 m. s. l.
15	Sept. 20, 1926	Pensacola, Fla	955	7.6 Ab. Nor.
16	Sept. 5, 1933	Brownsville, Tex	949	13.0 m. s. l.
17	July 25, 1934	Galveston, Tex	**975	5.9 m. s. l.
18	July 31, 1936	Panama City, Fla	964	6.0 m. s. l.
19	Aug. 7, 1940	Calcasieu Pass, La	974	4.8 m. s. l.
20	Sept. 23, 1941	Sargent, Tex	959	9.9 m. s. l.
21	Oct. 7, 1941	St. Marks, Fla	981	8.0 m. s. l.
22	Aug. 30, 1942	Matagorda, Tex	951	14.8 m. s. l.
23	July 27, 1943	Galveston, Tex	975	4.0 m. s. l.
24	Aug. 27, 1945	Matagorda, Tex	968	7.3 Ab. Nor.
25	Aug. 24, 1947	Sabine Pass, La	*992	3.6 m. s. l.
26	Sept. 19, 1947	Biloxi, Miss	968	11.1 m. s. l.
27	Sept. 4, 1948	Biloxi, Miss	*987	5.6 m. s. l.
28	Oct. 4, 1949	Freeport, Tex	978	10.4 Ab. Nor.
29	Aug. 30, 1950	Pensacola, Fla	979	5.5 m. s. l.
30	Sept. 5, 1950	Cedar Key, Fla	*958	5.1 Ab. Nor.

* Pressure data from *Monthly Weather Review.*
**An observed pressure of 986 mb. is reported in *Monthly Weather Review.* Data on file in the New Orleans Weather Bureau Office indicate that the central pressure was at least as low as 975 mb.

with a correlation coefficient of 0.66. If the data are analyzed according to equation (7), the resulting equation is

$$h_{max}=0.154\ (1019-p_0), \tag{10}$$

with a correlation coefficient of 0.68. Both curves are plotted on figure 1.

By comparing equations (9) and (10) with (6), it is seen that b is increased and B is decreased as p_n is increased from 1005 to 1019 mb. The correlation coefficient with the dependent data does not change significantly within this range of B, b, and p_n. (See Weatherburn [13], pp. 200–202, for a method of testing significance of correlation coefficients.)

A slightly higher correlation coefficient could have been obtained by using a much higher value of p_n and an exponent greater than 1.0 in equation (6). This, however, would be contrary to physical reasoning. As the storm tide rises to ever greater heights, the area over which the water can spread increases and the volume of water needed to produce a given rise in tide is greatly increased. It is evident that the curve which describes the relationship between the intensity of the storm and the height of the storm surge must ultimately curve downward toward the right. Although the reported tide height for the 1935 Labor Day storm suggests that this bending to the right occurs for storms with a central pressure slightly higher than 900 mb., the records from this storm are somewhat uncertain and it is not clear from the data presented here that this is the case. On the basis of the evidence presented in this paper, the straight line relationship appears to be the most reliable.

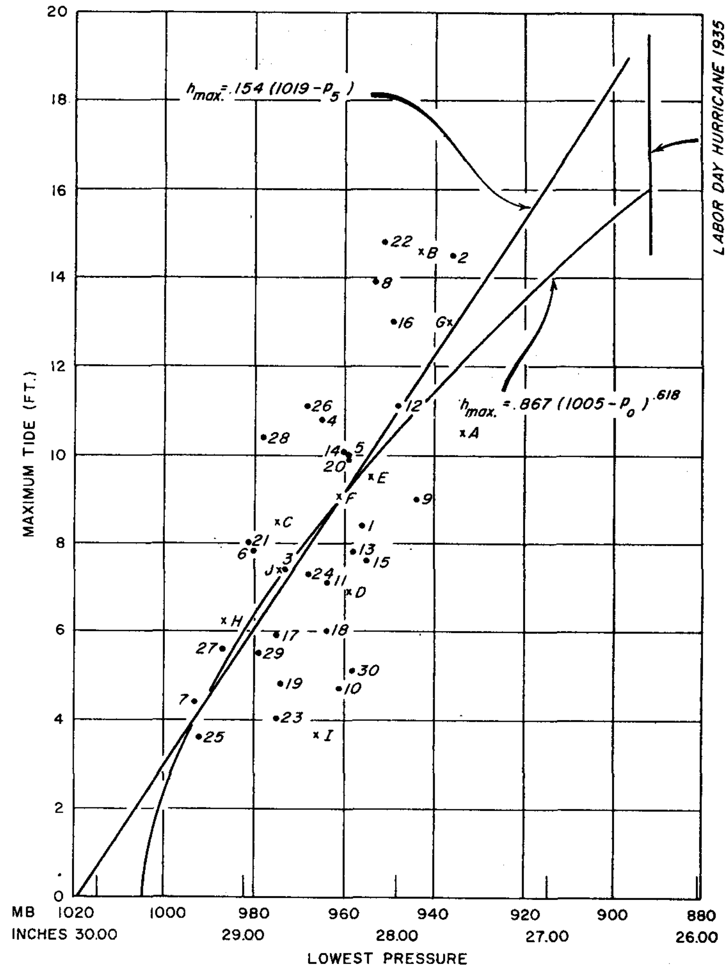

FIGURE 1.—Maximum tide or storm surge height on the open coast as a function of the central pressure. Dependent data are plotted as points and are identified with the data in table 1 by Arabic numerals. Independent data are plotted as crosses and identified with the data in table 2 by letters. The reports of the storm tide associated with the "Labor Day" hurricane of 1935 are somewhat indefinite as 15.0 to 20.0 ft. mean low water. This is shown as a range above mean sea level, as this hurricane had the lowest central pressure observed in the United States.

4. TEST ON ATLANTIC HURRICANE DATA

The tide range along the Atlantic Coast of the United States is much greater than in the Gulf and it is necessary to consider the difference between the observed and predicted tides, at the time of the maximum difference, in order to obtain reasonable homogeneity of the data when plotting a graph such as figure 1. When the difference is considered, many of the available points for the east coast fall near the line on figure 1. Most of the others fall well below the line.

The reason for this is not very difficult to find. Hurricanes which enter the Gulf of Mexico must come completely inland to escape from the Gulf. However, many of those which move up the east coast skirt the coastline and, even though the center or lowest pressure may be over land for a period of time, much of the storm circula-

TABLE 2.—*Lowest central pressure and storm surge height in Atlantic Coast hurricanes*

	Date	Location of highest tide on open coast	Central pressure (mb.)	Maximum storm surge height (ft.)
A	Sept. 18, 1926	Miami, Fla.	934	*10.5 m. s. l.
B	Sept. 21, 1938	Moriches, N. Y.	943	14.6
C	Aug. 11, 1940	Beaufort, S. C.	975	8.5
D	Sept. 14, 1944	Jones Beach, N. Y.	959	6.9
E	Aug. 26, 1949	Stuart, Fla.	954	*9.5 m. s. l.
F	Aug. 31, 1954, Carol	Woods Hole, Mass.	961	9.1
G	Oct. 15, 1954, Hazel	Southport, N. C.	937	13.0
H	Aug. 17, 1955, Diane	Southport, N. C.	987	6.2
I	Sept. 19, 1955, Ione	Morehead City, N. C.	966	3.6
J	Sept. 24, 1956, Flossy	Laguna Beach, Fla.	**974	7.4

*m. s. l. datum used because time of peak water level is unknown.
**Computed by Hydrometeorological Section of the Weather Bureau by the same method as that used for the other pressures reported in this table. See [12].

tion remains over water until after the storm loses hurricane intensity. Hurricane Ione of 1955 was a storm of this type. It is easy to understand that the storm surges associated with storms of this type might behave significantly differently from those hurricanes such as Hazel of 1954, which move completely inland, or from Gulf of Mexico storms. If only those east coast storms which move definitely inland are considered, it is found that the maximum surge data fit the empirical curve in figure 1 surprisingly well. The data from eight Atlantic storms of this type and two Gulf storms not used in the derivation of equations (9) and (10) are listed in table 2, and are shown in figure 1 by crosses identified by letters.

5. CONCLUDING REMARKS

The method described here is, of course, only the first step in the development of a storm surge forecasting system for hurricanes. It is worth noting, however, that this single meteorological parameter, central pressure, can account for approximately half of the total variability of the storm surge height on the open coast. The other meteorological parameters which could be easily considered in this way, the asymptotic pressure, the radius of maximum winds, the forward speed of the storm, and the angle with which the storm crosses the coast, when considered alone, do not make a significant improvement to the prediction equation. This is not because these parameters are unimportant, but because their effects are combined with those of local topography in such a way that their influence cannot be properly described by the methods used in this paper.

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